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Crop Ecosystem Responses to Climatic Change: Rangelands

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13.1 Introduction

Rangelands are defined as natural or semi-natural areas that produce plants grazed by wild and domesticated animals (Stoddart *et al.*, 1975). Included in this definition are unimproved grasslands, savannas, shrublands containing both grasses and woody plants, and hot and cold deserts (Fig. 13.1). These ecosystems occur on every continent except Antarctica and cover over 40%

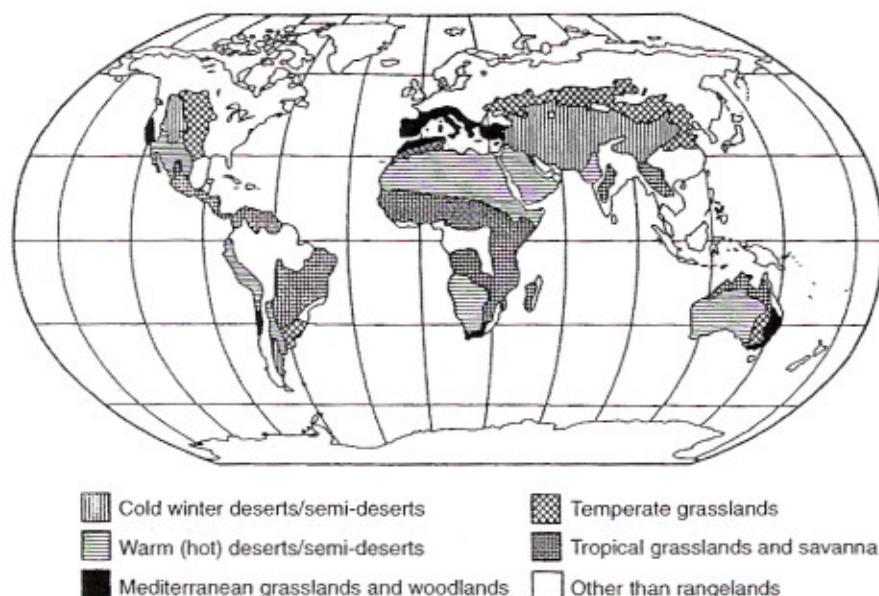


Fig. 13.1. Distribution of the world's rangelands. (Redrawn from Allen-Diaz, 1996.)

of the terrestrial land surface, with the greatest area in Africa and Asia (Allen-Diaz, 1996).

Environmentally determined rangelands are found where climate (chiefly water balance and minimum temperature) and soils interact to prevent occupation by dense stands of trees. Human activities, broadly classified as land use patterns, are another major determinant of the composition and structure of rangelands, and are an example of the alterations to earth considered here as global change. Land use changes include manipulation of fire regimes and other natural disturbances, adjustments in the intensity and duration of grazing, and fragmentation of once continuous rangelands by intensive agriculture and urbanization. Global change also includes changes in atmospheric composition, e.g. carbon dioxide concentration (CO_2) and resultant modifications in climate (temperature, precipitation). Some aspects of global change, like atmospheric and land use change, are well underway. Others, including shifts in climate, appear imminent.

Anticipated global changes could dramatically alter the extent and productivity of rangelands, but prediction and risk assessment are complicated by the diverse nature of these ecosystems and varied goals of managers (Campbell *et al.*, 1996; Stafford Smith, 1996).

1. Rangelands include a variety of plant species and growth forms (grasses, herbs, trees, shrubs) that respond in different ways and at different rates to the environment and to management inputs.
2. Rangelands are spatially and temporally variable. This natural variability increases the difficulty of discerning effects of management from those of the environment and environmental change (Campbell *et al.*, 1996; Stafford Smith, 1996).
3. Rangelands traditionally have been used to produce livestock, but these ecosystems provide other 'goods and services', including recreation, water and fuel wood (Fig. 13.2). Atmospheric and climatic change, combined with social, economic and demographic forces, will influence the product or combination of products for which rangelands are managed, and the intensity of future land use.

In this chapter, we review climatic and atmospheric changes expected during the 21st century and suggest some of the consequences of these changes for rangelands that are used primarily for grazing. Non-grazing uses of rangelands are briefly noted to illustrate reciprocal interactions between land use and climatic and atmospheric changes. Finally, we suggest management implications of global change.

13.2 Atmospheric and Climatic Change

The atmospheric $[\text{CO}_2]$ has risen during the past 200 years from approximately $280 \mu\text{mol mol}^{-1}$ in pre-industrial times to $360 \mu\text{mol mol}^{-1}$ today, and is projected to double over present-day concentration during the 21st century (Alcamo *et al.*, 1996). Other trace gases (CH_4 , N_2O , NO_x , CO) are also

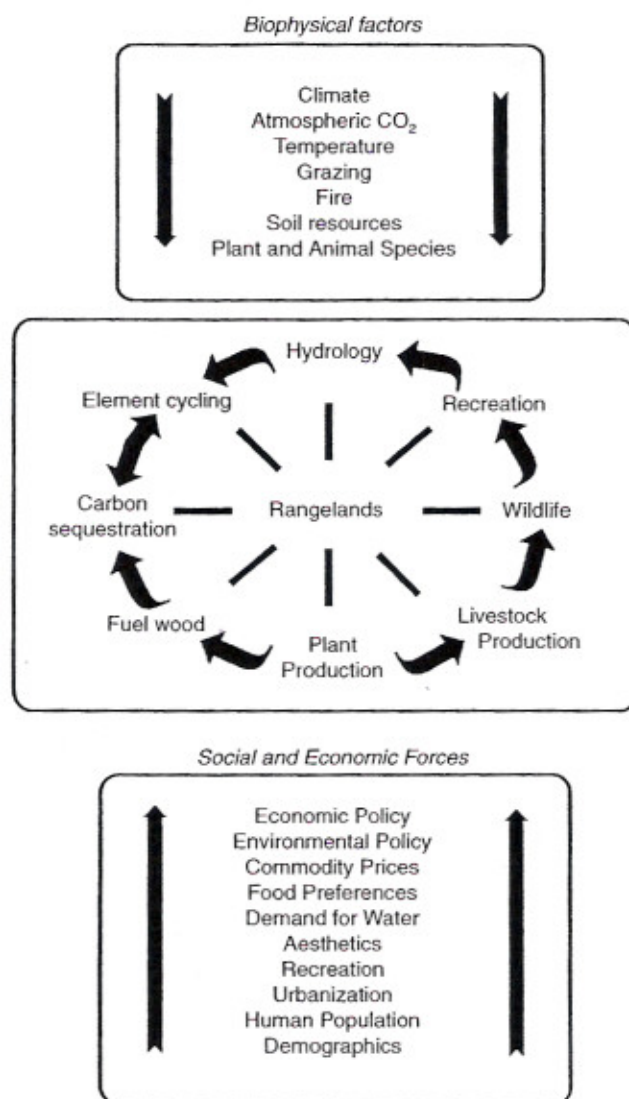


Fig. 13.2. Biophysical, social and economic forces influencing the goods and services for which rangelands are managed.

increasing rapidly, and will contribute to climate change. These increases result from human activities, especially combustion of fossil fuels, land use changes and agriculture. Increases in [CO₂] alone are predicted to warm the earth by 2–4.5°C by the middle of the 21st century, with a resultant increase in precipitation and storm intensity (Giorgi *et al.*, 1998).

Evidence from long-term climatic trends of the last century and modelled effects of [CO₂] (Giorgi *et al.*, 1998; Karl, 1998) suggests that warming will be greatest at high northern latitudes during autumn and winter. Consequently,

temperate grasslands of North America and central Asia may experience relatively more warming than tropical and subtropical grasslands of Africa, Australia, and South and Central America. In high and mid-latitudes, global warming may lead to increased winter precipitation. Predictions are more variable for the tropics, but many models predict more precipitation over India and southeast Asia. Inclusion of aerosols in modelling exercises reduces the change in temperature and precipitation patterns, and sometimes gives regional results that contrast with those obtained by modelling CO₂ responses alone (Giorgi *et al.*, 1998).

13.3 Impacts on Plant Productivity

13.3.1 Atmospheric [CO₂]

Most forage species on rangelands have either the C₃ or C₄ photosynthetic pathway. Over 95% of the world's plant species, including most woody plants, utilize the C₃ pathway. Photosynthesis in C₃ plants is not CO₂-saturated at the present atmospheric concentration, so increasing [CO₂] is predicted to stimulate carbon gain and productivity in these species (Drake *et al.*, 1997). Plants with C₄ photosynthetic pathways comprise fewer than 5% of the world's species, but are an important component of tropical and subtropical grasslands (Ehleringer *et al.*, 1997). The final steps of photosynthesis in C₄ plants occur in bundle sheath cells, where a highly efficient biochemical pump maintains CO₂ at concentrations that nearly saturate photosynthesis when atmospheric [CO₂] is near the current 360 $\mu\text{mol mol}^{-1}$ (Bowes, 1993). The C₄ metabolism does not, however, preclude photosynthetic and growth responses to CO₂ enrichment (Ghannoum *et al.*, 1997; LeCain and Morgan, 1998). Wand and Midgley (1998, unpublished results), for instance, measured a growth enhancement of 15% in C₄ grasses compared with 23% in C₃ grasses on doubling [CO₂] over the present level.

The photosynthetic pathway partially explains growth responses to CO₂, but CO₂ effects on transpiration and plant water-use efficiency (WUE; biomass produced per unit of transpiration) will be at least as important as photosynthetic metabolism in the future productivity of rangelands. Stomata of most plant species partially close as [CO₂] increases (Field *et al.*, 1995; Drake *et al.*, 1997). As this partial closure tends to reduce transpiration more than photosynthesis, leaf-level WUE (photosynthesis/transpiration) rises with [CO₂] (Polley *et al.*, 1996a). Reduced water loss and enhanced WUE can also be realized at the canopy level (Kirkham *et al.*, 1991; Nie *et al.*, 1992; Ham *et al.*, 1995), improving plant and soil water relations (Knapp *et al.*, 1994; Morgan *et al.*, 1994; Wilsey *et al.*, 1997), increasing plant production under water limitation (Owensby *et al.*, 1993a) and lengthening the growing season (Chiariello and Field, 1996). Water relation benefits of CO₂ enrichment largely explained the greater growth enhancement of C₄ than C₃ grasses in tallgrass prairie during dry years and the similar growth responses of C₃ and C₄ grasses under typically water-limiting conditions in shortgrass steppe (Owensby *et al.*,

1993a, 1997; Hunt *et al.*, 1996; Coughenour and Chen, 1997). Water relation benefits also apply to annual C₃ grasslands, where effects of elevated [CO₂] on plant production are more evident in drier years (Jackson *et al.*, 1995).

The ability to recover from defoliation is a major determinant of plant productivity and persistence on grazing lands. Recovery of grasses following grazing is controlled initially by re-mobilization of reserves, followed by photosynthetic gains (Caldwell *et al.*, 1981). To the extent that CO₂ enrichment increases photosynthesis and storage of reserves, it should enhance recovery from grazing. Plant response to defoliation depends on complicated interactions between grazing history and the environment (Milchunas *et al.*, 1988) and so effects of CO₂ enrichment are not likely to be simple. In a controlled environment, CO₂ enrichment had little effect on regrowth of grasses from three distinctly different grasslands (Wilsey *et al.*, 1997).

13.3.2 Temperature

Carbon dioxide enrichment and global warming are predicted to increase net primary production on most rangelands (Baker *et al.*, 1993; Parton *et al.*, 1995; Coughenour and Chen, 1997; Neilson *et al.*, 1998). Because of severe cold-temperature restrictions on growth rate and duration, warmer temperatures alone should enhance production in high- and mid-latitude and high-altitude rangelands (Baker *et al.*, 1993; Körner *et al.*, 1996; Rounsevell *et al.*, 1996). Warmer temperatures should also enhance the growth response of most C₃-dominated grasslands to rising [CO₂] (Long, 1991; Jones and Jongen, 1996; Coughenour and Chen, 1997; Drake *et al.*, 1997). This positive effect of warmer temperatures on production may be lessened, however, by an accompanying increase in evapotranspiration (ET) rate in drier systems such as the arid and semi-arid rangelands of Central and South America, Africa, the Middle East, Asia and Australia.

13.3.3 Precipitation

Current models yield widely varying estimates of future patterns in precipitation (Giorgi *et al.*, 1998), making it difficult to predict consequences of altered hydrological cycles for rangelands. Productivity on most rangelands is limited by water (Campbell *et al.*, 1997); therefore changes in the amount of precipitation will significantly impact these systems. Arid and semi-arid lands will be most sensitive to changes in precipitation, while usually wet mountain meadows will be minimally affected. Shifts in seasonal patterns of precipitation and predicted increases in storm intensity will probably have a greater impact on rangelands than shifts in precipitation amounts (Giorgi *et al.*, 1998). It is widely agreed that storm intensity will increase, resulting in greater runoff and concentration of water in smaller portions of the landscape. Such changes could reduce productivity or increase its heterogeneity (Campbell *et al.*, 1997; but see Williams *et al.*, 1998). The proportion of annual precipitation that falls

during winter months is predicted to increase at high to mid-latitudes (Giorgi *et al.*, 1998). Such a change in seasonality of precipitation, combined with warming (predicted to be greatest at high northern latitudes) and increased runoff resulting from more severe storms, could increase the incidence and severity of summer droughts in semi-arid grasslands of North America and Asia. Conversely, any increase in rainfall during the growing season will help to mitigate the desiccating effects of warmer temperatures.

13.3.4 Soil feedbacks

Long-term responses of rangelands to global change ultimately depend on the soil and its ability to supply nutrients, as well as water. Carbon dioxide enrichment appears to improve the efficiency with which plants utilize nutrients for growth (Stock and Midgley, 1995; Drake *et al.*, 1997). Interactions between $[CO_2]$ and nutrients are complicated, however, and plant responses to CO_2 enrichment may be constrained by low fertility, especially in relatively mesic environments (Sage, 1994; Stock and Midgley, 1995).

13.4 Impacts on Forage Quality

13.4.1 Plant-animal interface

Animal production on rangelands, as in other grazing systems, depends on the quality as well as the quantity of forage. Key quality parameters for rangeland forage include fibre content and concentrations of crude protein, non-structural carbohydrates, minerals and secondary toxic compounds. Ruminants require forage with about 7% crude protein (as a percentage of dietary dry matter) for maintenance, 10–14% protein for growth and 15% protein for lactation (Ulyatt *et al.*, 1980). Optimal rumen fermentation also requires a balance between ruminally available protein and energy (Dove, 1996). The rate at which digesta pass through the rumen depends on the fibre content of forage. Increasing fibre content slows passage and reduces animal intake.

13.4.2 Atmospheric $[CO_2]$

Based on expected vegetation changes and known environmental effects on forage protein, carbohydrate and fibre contents (e.g. Wilson, 1982; Owensby *et al.*, 1993b, 1996), both positive and negative changes in forage quality are possible as a result of atmospheric and climatic change (Table 13.1). Effects of CO_2 enrichment on crude protein content of forage, for example, are likely to be negative, for plant nitrogen concentration usually declines at elevated $[CO_2]$ (Owensby *et al.*, 1993b; Cotrufo *et al.*, 1998). Limited evidence suggests that the decline is greater when soil nitrogen availability is low (Bowler and Press, 1996; Wilsey, 1996), implying that rising CO_2 could reduce the digestibility of

Table 13.1. Potential changes in forage quality arising from atmospheric and climatic change.

| Change | Examples of positive effects on forage quality | Examples of negative effects on forage quality |
|---|---|---|
| Life-form distributions | Decrease in proportion of woody shrubs and increase in grasses in areas with increased fire frequency (Ryan, 1991) | Increase in proportion of woody species because of elevated CO ₂ , increases in rainfall event sizes and longer intervals between rainfall events (Stafford Smith <i>et al.</i> , 1995) |
| Species or functional group distributions | Increase in C ₃ grasses relative to C ₄ grasses with higher CO ₂ (Johnson <i>et al.</i> , 1993) | Increase in proportion of C ₄ grasses relative to C ₃ grasses due to higher temperatures (Campbell <i>et al.</i> , 1996) or changes in availability of water at elevated CO ₂ (Owensby <i>et al.</i> , 1997). Increase in plants poisonous to animals |
| Plant biochemical properties | Increase in non-structural carbohydrates at elevated CO ₂ (Read <i>et al.</i> , 1997). Increase in crude protein with reduced rainfall | Decrease in tissue nitrogen contents and increased fibre contents as result of reduced photosynthetic protein contents at elevated CO ₂ or higher temperatures (Sage <i>et al.</i> , 1989; Owensby <i>et al.</i> , 1993b, 1996; Soussana <i>et al.</i> , 1996; Read <i>et al.</i> , 1997). No change or decrease in crude protein in regions with more summer rainfall |

forages that are already of poor quality for ruminants. Such reductions in forage quality would have pronounced negative effects on animal growth, reproduction and mortality (Owensby *et al.*, 1996) and could render livestock production unsustainable unless animal diets are supplemented with N (e.g. urea, soybean meal). Concentrations of some of the plant products that are toxic to animals may also increase in a CO₂-rich environment.

13.4.3 Botanical composition and animal selectivity

Both positive and negative effects on forage quality are possible for individual species, but the total quantity of nutrients on offer to a grazing animal is determined by the relative abundances of plant species in vegetation. Carbon dioxide enrichment initially reduced crude protein content of both species in a grass-clover mixture, but the protein content of the entire sward eventually increased at elevated [CO₂] because of a greater overall proportion of high-N clover (Schenk *et al.*, 1997). Similar effects are likely on rangelands, which contain complex mixtures of species of differing ecology and forage quality.

Ultimately, the quality of livestock diets is determined both by the quality of the forage on offer and by selectivity of animals during grazing. Research

efforts have focused primarily on changes in forage quality to the near exclusion of potential changes in grazing behaviour by animals. Selective grazing is a significant feature of livestock on rangelands, where utilization is much lower than in intensively managed pastures. There is a need, therefore, to determine whether higher temperatures or other global changes will alter grazing behaviour and whether changes in grazing behaviour could compensate for a general decline in forage quality.

13.5 Impacts on Plant Species Composition

13.5.1 Importance of botanical composition

Research has emphasized global change effects on plant and ecosystem production and water balance, but changes in plant species composition could have at least as great an impact on the goods and services that rangelands provide as might changes in production. Rangelands are used primarily for grazing. For most domestic herbivores, the preferred forage is grass. Other plants, including trees, shrubs, and other broadleaf species, can lessen livestock production and profitability by reducing availability of water and other resources to grasses, making desirable plants unavailable to livestock, or physically complicating livestock management, or poisoning grazing animals (Dahl and Sosebee, 1991). The functioning of ecosystems can also be changed by addition or loss of plants which greatly affect disturbance regimes or soil resource (Vitousek, 1990). The spread of the annual grass *Bromus tectorum* (cheatgrass) through the intermountain region of western North America, for example, altered the frequency and timing of wildfires, and reduced establishment of perennial herbaceous species by pre-empting soil water early in the growing season (Young, 1991).

13.5.2 Environmental controls on species composition

The plant species composition of a region is largely determined by climate and soils, with fire regime, grazing and other land uses more locally important. The primary climatic control on the distribution and abundance of plants is water balance (Stephenson, 1990), especially on rangelands, where species composition is highly correlated with both the amount of water that plants use and its availability in time and space (Parton *et al.*, 1994).

13.5.3 Atmospheric [CO_2]

Carbon dioxide enrichment should slow canopy-level evapotranspiration (ET) (Drake, 1992; Ham *et al.*, 1995) and the rate or extent of soil water depletion (Kirkham *et al.*, 1991; Owensby *et al.*, 1993a; Jackson *et al.*, 1994; Field *et al.*,

1997), unless stomatal closure is compensated by atmospheric or other feedbacks. Plants that are less tolerant of water stress than current dominants should be favoured. Three general mechanisms may contribute to compositional changes.

1. By increasing WUE, CO₂ enrichment increases maximum leaf area and competition for light (Woodward, 1993). These changes should favour progressively taller and less drought-tolerant plants (Smith and Huston, 1989).
2. Slower ET minimizes the decline in soil moisture during periods between rainfall events. Wetter soils should enhance reproduction and survival of drought-sensitive species (Jackson *et al.*, 1995; Chiariello and Field, 1996).
3. By fostering wetter soils, CO₂ enrichment may increase deep percolation of water and favour more deeply rooting plants, like trees and shrubs, at the expense of shallow-rooting grasses (Polley *et al.*, 1997). Percolation below 1 m in California sandstone grassland increased by 20% on doubling [CO₂], despite a concomitant 20% increase in plant biomass (Jackson *et al.*, 1998).

Paradoxically, species composition may be more sensitive to a CO₂-mediated decrease in transpiration on relatively mesic rangelands (Table 13.2). Water savings are reduced when leaf area or soil evaporation increase – changes that are more likely on dry rangelands with open vegetative canopies than in mesic systems with closed vegetation.

Benefits of CO₂ enrichment to droughted plants may not be restricted to slower ET and soil water depletion. Higher [CO₂] can also extend seedling survival during drought (Polley *et al.*, 1996b). The full impact of this effect remains to be established, but density of the dominant species in California annual grassland (*Avena barbata*) was 87% greater at elevated than ambient [CO₂] during a dry year, apparently because of greater survivorship (Jackson *et al.*, 1995).

13.5.4 Precipitation regimes

A warmer climate means a more intense hydrological cycle, accompanied by an increase in the frequency of extreme events such as heavy rains and

Table 13.2. Predicted effects of CO₂ enrichment on soil water content and components of the hydrological cycle on arid and relatively mesic rangelands.

| Parameter | Mesic rangelands | Arid rangelands |
|-------------------------|------------------------------|----------------------|
| Transpiration/leaf area | Reduced | Reduced |
| Leaf area | Increased during dry periods | Increased |
| Total transpiration | Reduced, especially when wet | Small reduction |
| Soil evaporation | Little change | Possible increase |
| Percolation | Increased | No change |
| Runoff | Possible increase | No change |
| Soil water content | | |
| Shallow | Increased | Small or no increase |
| Deep | Potentially increased | No change |

droughts. Changes in the timing and intensity of rainfall will be especially important on arid rangelands, where plant community dynamics are 'event-driven' (Walker, 1993; Wiegand *et al.*, 1995) and the seasonality of precipitation determines which plant growth strategies are successful (Westoby, 1980). The timing of precipitation also affects the vertical distribution of soil water, which controls the relative abundances of plants that root at different depths (Ehleringer *et al.*, 1991; Weltzin and McPherson, 1997).

13.5.5 Temperature

Temperature influences botanical composition in several ways. Global warming, for example, may favour C_4 over C_3 grasses (Field and Forbe, 1990; Epstein *et al.*, 1997) by increasing the minimum daily temperature during the growing season (Teeri and Stowe, 1976) or by increasing photorespiration and reducing quantum yield in C_3 species (Ehleringer *et al.*, 1997). However, the effect of CO_2 enrichment on quantum yield is opposite to that of higher temperature. Doubling $[CO_2]$ can, in fact, more than offset the decline in quantum yield of C_3 plants caused by a $2^\circ C$ rise in temperature (Long, 1991) and render C_3/C_4 distributions and abundances relatively insensitive to the effects of higher temperature on quantum yield.

Extreme temperatures could become more frequent with global warming and could influence species distributions and abundances by affecting plant reproduction, competitive ability or survivorship. Plant responses to extreme temperatures appear to be species-specific, and thus are difficult to predict (Coleman *et al.*, 1991; Bassow *et al.*, 1994).

13.5.6 Interactions between temperature and $[CO_2]$

Many of the influences of higher temperature and $[CO_2]$ on plants are not additive, so combined effects are not readily predictable from knowledge of individual effects (Bazzaz *et al.*, 1996). Neither do plants respond as predictably to temperature or CO_2 as to other factors or resources (e.g. water, nitrogen). Species within a given growth form responded similarly to changes in nutrient availability and light in tussock tundra, but showed no consistent response to higher temperature (Chapin *et al.*, 1995). Progress in predicting the response of vegetation to a warmer climate may require a better understanding of indirect effects of temperature on soil resources to which species respond more predictably (Chapin *et al.*, 1995). Warming in montane vegetation produced species changes apparently explained by temperature effects on soil moisture (Harte and Shaw, 1995).

13.5.7 Changes on global and regional scales

Long-term and global-scale responses of vegetation to higher $[CO_2]$ and temperature have been estimated by modelling the equilibrium distribution of

earth's vegetation from hydrological and plant physiological parameters (Woodward, 1993; Neilson, 1995; Haxeltine and Prentice, 1996). Both the MAPSS (Neilson, 1995) and BIOME3 (Haxeltine and Prentice, 1996) models predict a mean increase in leaf area index of earth's vegetation following a doubling in $[\text{CO}_2]$ (Neilson *et al.*, 1998). The total area of grassland and shrubland in simulations either remains unchanged or increases by as much as 27%, depending on the scenario modelled.

Regional-scale estimates of climate change and associated impacts are highly uncertain. Climate models generally predict a greater-than-average increase in temperature in southern Europe and central North America, accompanied by reduced precipitation and soil moisture during summer (Giorgi *et al.*, 1998). Precipitation is particularly difficult to predict at regional scales, but there is some consensus that winter precipitation will increase at mid-latitudes. In regions like the southwestern USA, increased winter precipitation could favour large and deep-rooting woody plants over shallow-rooting warm-season grasses (Weltzin and McPherson, 1997). Wetter winters during the recent past may already have contributed to invasion of desert communities in Arizona, USA, by red brome (*Bromus rubens*), a winter annual (Betancourt, 1996) and of grasslands in the southwestern USA by shrubs (Neilson, 1986).

13.5.8 Local and short-term changes

The ability to predict vegetation change declines at lower spatial and temporal scales, i.e. as greater details of vegetation dynamics are required. There are at least two reasons. Firstly, transient responses of vegetation to global change depend on how quickly various species can disperse propagules across landscapes that are sometimes fragmented. Secondly, disturbances, biotic interactions and other local-scale processes become more important in vegetation dynamics at lower spatial and temporal scales.

Of necessity, field experiments with different CO_2 concentrations and temperatures are conducted at local scales, where variability in vegetation is high. Nevertheless, patterns of vegetation response are beginning to emerge.

1. Directional shifts in the composition of vegetation occur most consistently when global change treatments alter water availability (Owensby *et al.*, 1993a; Harte and Shaw, 1995; Chiariello and Field, 1996).
2. Carbon dioxide enrichment usually alters species abundances in multi-species communities, even when there is no net stimulation of total biomass (Körner, 1996).
3. Plant response to $[\text{CO}_2]$ or temperature in multispecies communities is not readily predictable from the response of individually grown plants or from plant morphology or physiology (Chapin *et al.*, 1995; Körner, 1995; Leadley and Körner, 1996). This occurs because expression of the multiple direct and indirect effects of $[\text{CO}_2]$ and temperature on plant growth and development depends on complex interactions among other environmental and biotic factors.

4. As a consequence of the above, species response to $[\text{CO}_2]$ and temperature is often highly context-specific (Roy *et al.*, 1996).
5. Vegetation dynamics may be as sensitive to the secondary or indirect effects of atmospheric and climatic change as to direct effects of global changes on plant growth. In closed-canopy vegetation in particular (Roy *et al.*, 1996), changes in dominance may correlate better with changes in plant morphology, development and phenology than with more direct effects of $[\text{CO}_2]$ or temperature on growth (Reekie and Bazzaz, 1989). At larger scales, effects of atmospheric and climatic change on fire frequency and intensity and on soil water and N availability will probably influence botanical composition to a much greater extent than global change effects on production.
6. Effects of CO_2 enrichment on species composition and the rate of species change will probably be greatest in disturbed or early-successional communities where nutrient and light availability are high and species change is more highly influenced by growth-related parameters (Arnone, 1996).
7. Rangeland vegetation will be influenced more by management practices (land use) than by atmospheric and climatic change. Global change effects will be superimposed on and modify those resulting from land use patterns in ways that are as yet uncertain.

Vegetation changes of greatest concern to managers are those that are essentially irreversible within the constraints of traditional management, and that fundamentally alter rangeland structure and function. Such shifts between 'alternate stable states' of vegetation usually occur when changes in soil properties, disturbance regimes or animal populations remove limitations on increasing plants or create or enforce limitations on current dominants.

Vegetation change can occur gradually, as when woody plants replace grasses following prolonged grazing, but can also occur rapidly, as when a threshold of soil loss is crossed that prevents continued dominance by current occupants of a site (Friedel, 1991). Gradual vegetation change is more common on mesic grazing lands, whereas rapid or 'episodic' change is more prevalent on arid rangelands (Walker, 1993; Wiegand *et al.*, 1995). Changes in precipitation could cause rapid shifts in vegetation on arid rangelands, but global change will more often influence the susceptibility of vegetation to other factors than directly alter the 'state' of vegetation. Unfortunately, there is no universal method for recognizing the proximity of rangelands to thresholds of vegetation change or for predicting global change effects on the susceptibility of rangelands to change.

13.6 Management Implications

13.6.1 Rangelands managed for livestock production

Global change has implications for both land managers and national or regional policy-makers. Some effects of atmospheric and climatic change can be accommodated quite easily by each group. Others will require changes in practices and policies. Anticipated changes in forage quality and quantity, for

example, are not likely to be novel, and could be dealt with by feeding supplements, albeit at an economic cost. Modest shifts in primary productivity could be accommodated by adjusting stocking rates, while climatic impacts on pests and diseases might require a shift in livestock type or breed. On the other hand, innovation and changes in management practices may be required to deal with substantial changes in plant composition, including invasions by different forage species or changes to non-forage species such as trees and shrubs.

These factors could create systematic changes in enterprise profitability, with consequences for regional economies. A simulation study of a beef cattle ranch in northern Australia (Campbell *et al.*, 1997) demonstrated the relative effects of different factors on whole-enterprise profitability (Table 13.3). The precise figures should be given no significance, because they are strongly dependent on enterprise, management and markets, but they make two important points.

1. Changes in pasture composition may have a far greater effect on profitability than changes in plant productivity.
2. Modest shifts in prices will affect profitability as much as other changes.

Rangeland managers already must cope with highly variable physical and marketing environments. Any factor that reduces variability should simplify management and potentially increase profitability. A decrease in interannual variability of forage production, for instance, could benefit profitability, whether the decrease results from changes in plant growth patterns or from

Table 13.3. Simulated impact of global changes on profitability of a commercial cattle ranch in northern Australia (Campbell *et al.*, 1997, supplemented with more recent unpublished simulations). Simulations ran for 100 years with realistic weather and with constant management strategy, costs and prices. Results are the change from a baseline simulation for an enterprise with annual turnover of Aus\$450,000.

| Parameter impacted | Implementation | Change in annual profit (Aus\$'000s) |
|--------------------|--|---|
| Plant productivity | Assumes the maximal realistic effect of CO ₂ on transpiration, nitrogen and radiation use efficiency (a substantial part of the benefit results from reduced interannual variability) | +37 |
| Forage composition | 20% reduction in perennial grasses | -60 |
| Tree/grass balance | 2.5% increase in tree basal area with consequent reduction in forage production | -107 |
| Forage quality | 10% decrease in liveweight gain per year (this could be compensated by supplements) | -35 |
| Sale prices | 10% increase in sale prices | +82 |
| Transport costs | 10% increase in direct fuel costs | -2 |

changes in climate (Campbell *et al.*, 1997). On the other hand, profitability could be reduced by climatic changes (such as a greater incidence of drought) that increase variability in forage production. Given the variety of environments on rangelands, we should expect the relative importance of various global change effects to differ among regions. Indeed, interannual variability is of greater concern on arid than mesic rangelands, while the anticipated decline in forage quality will be a greater problem in infertile than fertile environments (Table 13.4).

At the regional scale, then, it is clear that there could be systematic changes in profitability. We are, however, only beginning to acquire the information and to develop the tools necessary to predict these changes reliably. The simulation approach described above could be expanded to consider regional implications of changes for rangeland profitability. Baker *et al.* (1993) described such an effort for the western USA, while Campbell *et al.* (1996) described a general approach for assessing the management implications and economic consequences of global change. To provide relevant information, global change studies must focus on issues appropriate to different regions. In general, however, global change effects on diet quality and vegetation composition are the two areas of poorest knowledge.

13.6.2 Rangelands managed for other uses

Rangeland issues of greatest concern to society will differ among regions and may not include livestock production. Results of an informal survey of policy-makers in northern Australia and the western USA, for example, clearly demonstrate that livestock productivity is but one of a suite of concerns in a changing world (Table 13.5). In general, commercial rangelands of the world are tending towards less intensive grazing by livestock, with increased emphasis on other uses such as urbanization (USA), game ranching (South Africa, USA) and the transfer of former homelands to indigenous peoples

Table 13.4. Atmospheric change and its management implications for rangelands that continue to be used for grazing.

| System description | Fertile | Infertile |
|--------------------------|---|--|
| Subhumid/ subtropical | Drop in forage quality, but probably easily compensated for at a cost with supplements; areas to be taken out of production risk of shifting tree/grass balance | Drop in forage quality most significant. May cause marginal |
| Arid | Increase in WUE and consequent reduction in variability of plant production between years significantly improves reliability and profitability | Minor reduction in variability and increase in production efficiency |

(South Africa, Australia). Global change effects on species composition are likely to be more important than those on production in these rangelands (Table 13.6). Meanwhile, rangelands utilized for subsistence (such as those in the Sahel, the Thar Desert in India, and the margins of China) are being used more intensively to meet the needs of expanding human populations. Changes in plant production are the dominant concern in these areas.

Table 13.5. Issues raised by policy-makers for commercial rangelands of Australia and USA (unpublished data, Mark Stafford Smith, Jack Morgan).

| Australia | USA |
|---|--|
| Woodland thickening | Aging of agricultural population |
| Costs and impacts of supplementary feeding | Urbanization and increasing land use conflict |
| Industry viability on marginal lands – grazing vs. cropping | Consumptive vs. non-consumptive uses of wildlife |
| Fire frequencies and degradation risks | Recreation interests |
| Opportunities for carbon sequestration | Water quality and supply |
| Changing drought frequency and tax incentives for managing it | Plant species migration |
| Regional conservation of biodiversity | Government fees and incentives on public and private land uses |

Table 13.6. Implications of global change for regions where land use is dominated by intensification vs. land abandonment.

| General land use pressure | Implications of global change |
|---|---|
| Intensification (Africa, China, Asia, etc.) | Rising population places more intensive demands on food production Effects of atmospheric changes will vary across systems (see Table 13.4) and depend greatly on regional climate change. Effects on plant production will be important, but compositional change towards woody plants is not likely to be a problem, given human needs for fuel wood |
| Reduction in grazing (USA, Australia, Europe, some of S. Africa, some of S. America) | Abandonment or substantial reduction in stocking rates tends to reduce the amount of rangeland used for live-stock production and the intensity of land use. Both changes lead to greater game ranching, tourism, nature conservation, etc. Most direct atmospheric effects will be unimportant for primary land uses (e.g. tourism, hunting), although non-domestic grazers may suffer from diet quality reductions. Increases in trees and shrubs could decrease fire, while greater fuel production could increase fire frequency |

13.6.3 Management implications – summary

On commercial rangelands, profitability may change and management may have to be adjusted to accommodate vegetation change. The general need to optimize stocking rates will continue to be essential, and flexibility in management will remain important. The rate at which management must adjust to accommodate climatic and atmospheric change will be considerably slower than adjustments required to track market fluctuations and other aspects of the normal operating environment. The situation will differ on marginal rangelands. On the productive margins, land use pressures are likely to cause substitution by attempts at cropping. On the least productive margins, changes in profitability may tilt land use decisions in favour of or against grazing, depending on local conditions. In general, however, land use decisions on marginal rangelands will be driven by factors other than global change effects on plant and animal productivity – these will simply serve to enhance or delay existing trends.

13.7 Conclusions

Of the global change effects discussed here, none is potentially more significant for rangelands than a shift in botanical composition. Yet species change is also among the most difficult of global change effects to predict, because it is highly context-specific at the spatial and temporal scales of field experiments. What is needed is a more systematic examination of the ways in which global changes interact with and modify the characteristics of plants that determine their responses to disturbances and environmental conditions. Vegetation change will probably be more closely coupled to changes in soil resources than to immediate physiological responses of plants to $[CO_2]$ concentration or temperature. Understanding how soil resources respond to global change is thus also a priority. Predicting and adapting to these changes are among the major challenges faced by rangeland scientists, land managers and policy-makers.

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